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Appropriateness' of the Use of Tensile Membrane Structures in Hot Arid Regions

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ABSTRACT: Today, with the vast technological progress and the deep understanding of our environment, and the insisting need to reduce energy consumption to save our natural resources there have been a shift in thinking and the need for a sustainable environmentally friendly architecture has evolved. The need of new materials and structures that fulfil the occupant's needs and comfort, has the architectural beauty and attraction and be environmentally friendly has become a necessity.

Although, tensile membrane structures (TMS) are relatively new as a structural material, they have been widely used in many architectural projects that were mainly considered as architectural statements and landmarks. Form finding and structure analysis of such structures has become an established discipline, however, their environmental understanding and behaviour are still in its infancy. This paper considers the appropriateness of the use of TMS in hot arid regions through a review of some of the built environment successful built examples.

Keywords: Tensile Membrane structures; Internal comfort; Sustainable Architecture

1. INTRODUCTION [arial10 capitals]

The completion of significant numbers of TMS in different parts of the world during the last thirty years has made them part of the contemporary architectural vocabulary [1]. Extensive research on the analysis of their complex three-dimensional shapes followed the efforts of membrane manufacturers to create ever stronger and durable materials 2, is allowing increasingly more daring and complex structures to be built. The greatly improved life expectancy of the membranes eroded the early beliefs that their domain of application was limited to temporary shelters and opened new markets for these innovative structures.

However, as mentioned earlier TMS has been used for permanent buildings for so long, understanding of the environmental behavior, thermal performance and impact on the spaces such structures enclose is still in its infancy 3,4. The environmental behavior of membrane skins differs greatly from that of conventional structures 5,6,8. Thus their environmental behavior needs to be properly explored in order to offer improved comfort to the occupiers of these structures 5.

2. ENVIRONMENTAL BEHAVIOUR

Generally, textile membrane surfaces react very rapidly to external energy influences because of their low thermal mass. This, combined with low thermal resistivity, generally means that cooling due to winter thermal losses and excessive heating in summer by solar radiation of the inner space can only be controlled by significant expenditure on heating and cooling plant. Considerate design of the form found curvature and external/internal form of the membrane structure also offers a means of providing appropriate levels of comfort within the enclosed space.

Early quantitative research into the environmental behaviour of spaces enclosed by fabric membranes pointed out to the need for developing a technique for investigating the indoor climate of such structures. Adopting the simple steady state technique, which was initially designed for investigating the internal climate of more conventional buildings, proved to be inappropriate5. Such techniques are based on the use of U- values and shading coefficient, which do not have a significant affect on thin translucent fabric structures. There are a number of different environmental, climatic factors and material properties affecting the environmental behaviour of fabric structures as shown in Figure 1.

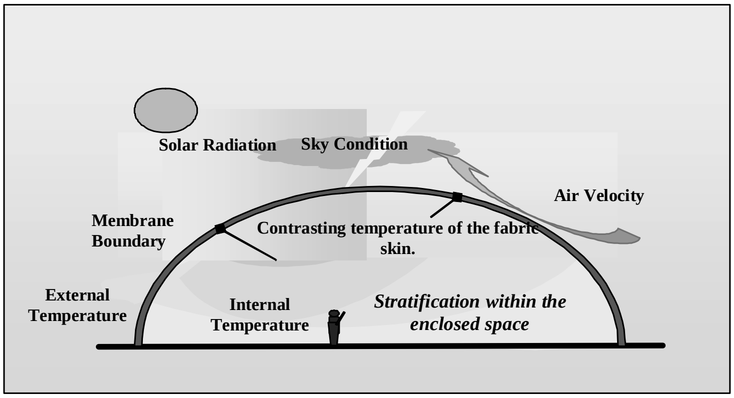

Figure 1: Stratification of air in tensile membrane enclosures

3. INCREASING UPTAKE OF FABRIC STRUCTURES

Each year, the trend towards using membranes in an architectural context grows stronger. Many leading edge construction projects have a tented element or elements. Some, such as the Burj Al-Arab hotel in Dubai shown in Figure 2, would not even appear the same concept without the membrane shade structure soaring vertically, integrated into the shell of the building for a major part of the overall aesthetic. Many membranes are used, not just to provide cover, but to fundamentally change the nature of the area beneath, and to stand as a landmark in their region. This makes it a very interesting material to be explored by both the architect and the building industry.

Figure 2: Burj Al-Arab Hotel, Jumeirah Beach, Dubai; (a), (b) Source: Sky span [www.skyspan.com] [15]; (C) [16]

However, as membrane enclosures were becoming a competitive alternative to traditional construction methods, their wide acceptance by the building industry remained impaired by their relatively poor thermal performance and the difficulty associated with predicting their environmental behaviour. This scepticism originated mostly from the historical development of modern TMS. Early experiments with fabric enclosures were mainly focused on temporary structures such as exhibition halls or seasonal covers for sports facilities. These types of applications made full use of their impressive structural efficiency to create wide span enclosures and of the ease with which these large shelters could be transported to the site and erected.

Designers paid little attention to the environment inside these enclosures as discussed earlier in this paper, as the temporary nature and the type of activities they sheltered allowed rather loose comfort criteria for the internal spaces. The evident complexity of modelling the environment inside the non-Cartesian geometry of the enclosure added to the lack of understanding of the thermal properties of the building skin, which had little in common with traditional construction materials. Intuition would suggest that the thermal conditions inside a free form space enclosed by a millimetre thick translucent skin were unlikely to reach the standards of those encountered in an air-conditioned traditional office environment Figure 1.

Sporadic attempts were made to evaluate the thermal performance of the membrane envelopes using approaches adopted for glazing systems which have complete different optical properties than TMS as shown in Figure 3. These models paid little attention to the specific nature of the membrane skin and of the topology of the space it enclosed.

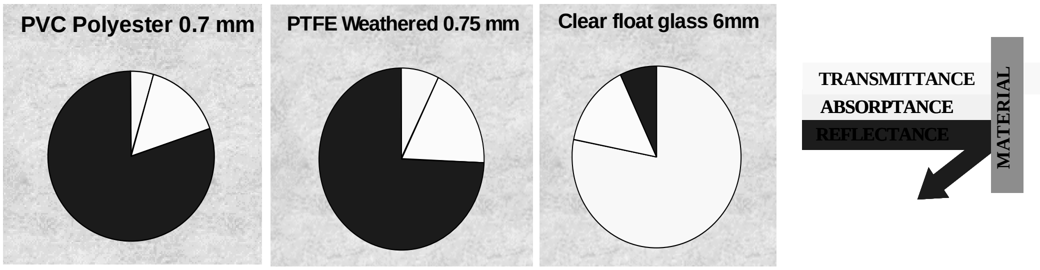

Figure 3: Optical Properties of TMS in Comparison to Clear Float Glass 6mm

4. FABRIC TOPOLOGY AND MANIPULATION OF THE INTERNAL ENVIRONMENT OF A FMS ENCLOSURE

A simple tent may be sufficient to filter out the worst of adverse weather conditions, although the response of a simple tent to the external weather conditions may be too fast to maintain comfort. Thus, when designing with fabric membrane skins it is reasonable to consider them as an environmental “filter” rather than as “barriers” to the weather.

The topology and form of the tensile structure can be used to alter the quantity and direction of solar radiation entering the enclosure. These can also be used to modify the airflow underneath the structure and in its vicinity. Fabric membranes can be merely used for creating an intermediate climate or meso-climate that acts as a buffer between the external climate and the environmentally controlled interior of the building to moderate and regulate them rather than shutting it out completely 8.

The membrane form and orientation and the associated thermal mass (walls, floors, terraces, water pools, fountains, etc.) can be designed to suit different seasons and climates. For example, in winter the structure should be designed to maximise the absorption of daytime solar energy through solar absorption by thermal mass (buildings, terraces, paving, patios, walls, etc...) and reradiate it into the enclosure and at the same time to screen chilling wind. At night it should be sufficiently air tight in order to use the absorbed daytime radiation to warm the space at night and should be designed to prevent re-radiation of heat absorbed and its escape to the night sky.

In summer, the opposite should occur, as the fabric structure should be shaped and oriented to provide shade by screening solar radiation and the fabric material chosen should be such that it absorbs and transmits a minimum amount of solar heat into the space, and work in conjunction with thermal mass distributed within the enclosure to stabilise temperatures. It should be designed with a number of different openings so that the internal heat finds a place to escape at night through the openings, or it could also be folded at night, so as to encourage ventilation and escape of the heat through radiation that is stored in the thermal mass during the day to the night sky. This is easily achieved in climates with clear night skies. Also, in sunny parts of the world, the shape of the structure can also be oriented such that it is parallel to the sun’s arc across the sky, providing shade throughout the day.

A number of traditional passive cooling systems can be effectively used in conjunction with fabric membranes, such as: evaporative cooling using water cascades, mist sprays or fountains, cooling towers, fans, stack effect and self shading. All of these strategies can be used to enhance the benefit of TMS in hot climates.

Many membranes are used, not just to provide cover, but to fundamentally change the area beneath. 'Form follows Function' is a modernist ideal. With the membrane structure, the two concepts are indivisible.

There have been many architectural projects making use of the unique nature of TMS to enhance the environment within the enclosures. The structure can be shaped and oriented to allow maximum solar gain in winter by exploiting the low angle of the sun as is used in more conventional buildings. In summer the form of the building can provide shade by screening occupants from solar radiation from the higher overhead arc of the sun. To study membrane structures clearly we need to look at some of the successful examples erected in the world, which explored the form of the structure to enhance the environment within their enclosure. There follow, some examples that have used different techniques for enhancing the environmental behaviour of their enclosures.

4.1 Haj-Terminal in Jeddah

The Haj Terminal, part of the King Abdul Aziz International Airport in Jeddah, Saudi Arabia is located approximately 70 km west of the Holy City of Mecca. The structure was erected to provide comfort for the pilgrims attending the Haj by protecting them against the heat of the desert sun. This project is considered one of the largest and most important projects that has utilized conical membranes to provide shelter to its occupants and protect them against the harsh conditions of the desert climate, utilizing a number of different techniques to enhance the climate within the semi-enclosed space.

Utilizing a fabric structure for this offered superior environmental properties as compared with more conventional structures. A tensile structure using Teflon coated glass maintained its surface temperature within a few degrees of the ambient air, by reflecting most of the sun’s heat 1. The white fabric reflects 75% of radiation 9, thus utilizing one of the main features of TMS which is reflection of the suns heat. The fabric’s translucency made artificial light unnecessary during the daytime, and thus energy use would be dramatically reduced.

Along the central spine, entry road, ten identical modules (arrays of cones) were arranged with five modules on each side of a central roadway, with provision for an additional 5 modules on each side. Each module contains 21 semi-conical, square, fabric roof units with a side length of 45 metres stretched and formed by 32 radial cables. Forty five metre high steel pylons located on a square 45 metre grid support these modules. The steel cables radiate from the top of columns to a central steel tension ring of 3.96m in diameter, to which they are attached as shown in Figure 4(b).

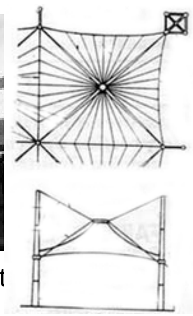

Figure 4: (a) Haj-terminal at King Abdul Aziz international Airport Hafsteinsson [17] (b) Typical unit of Haj Terminal fabric roof;

The columns taper from 2.5m at their base to 1m at the top as shown in Figure 4(b). The twin tented area covers about 420, 000 sq.m of land, and is by far the largest roof cover in the world 10. The columns have been spaced far apart to give a very open feeling to the large supported area and allow maximum flexibility in planning these areas 1.

The large form and height of the Teflon coated fibreglass fabric unit of the roof, promotes circulation of air from the open side of the supported area up to and through the open steel tension ring located at the top of the roof unit. Fan towers placed intermediately between columns enhance air circulation, keeping the temperature down. Acoustical problems are diminished due to roof height and material. Due to its low heat transmission and high reflection, the fabric allows the sun to cast a warm light over the area below.

The main idea behind having a semi-enclosed space is to allow for natural and cross ventilation to take place in the semi-enclosed space, to add to the comfort of the occupants. The climate in the construction place is usually hot dry and this is when the pilgrimage takes place in Mecca. Under the landscaped central mall are located two large exhaust fans for each module to draw off the exhaust fumes of the buses that transports the pilgrims. The project was successfully finished in 1982. The final project is shown in Figure 5.

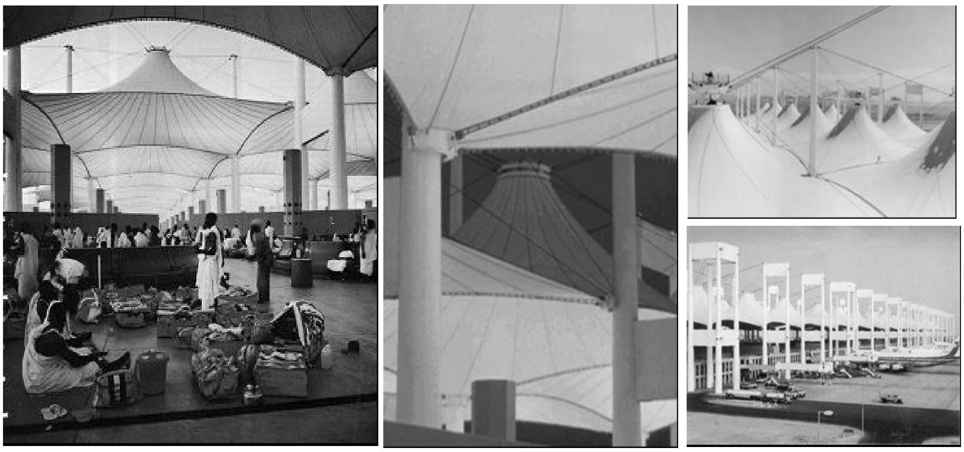

Figure 5: Interior and exterior views of the Haj Terminal in Jeddah

4.2 The Bioclimatic Rotunda in Expo' 92, Seville

This is a mega project where engineers and architects worked closely from the earliest stages of the design and which represents one of the largest examples of the climatic conditioning of urban spaces. The entire project lies within a general framework of climatic conditioning of the outdoor spaces at Expo 1992 in Seville, Spain.

A pilot project "Bioclimatic Rotunda" was set as a full scale experimental support for testing and evaluating different systems designed for the climatic treatment of outdoor spaces. The rotunda was monitored for two consecutive summers in 1989 and 1990.

The project was meant to be for the Expo' 92 which was to take place during the months of June to September; the climatic conditions in Seville are very harsh at that time. Temperatures can reach over 40º C combined with high values of solar radiation. The research sought to develop an efficient and realistic methodology for the thermal conditioning of outdoor spaces within a series of aesthetic, economic and functional constraints 11, which the rotunda is a part of.

The bioclimatic rotunda is considered as a rest zone in which natural air cooling techniques were tested. The rotunda has three levels linked by stairways and forms a square with sides of 31 metres as shown in Figures 6 and 8. The two lower levels contain the areas intended to be used by the occupants, forming two concentric circles with diameters of 24 and 16 metres respectively, with difference in height between the two levels of 80cm. Water cascades fall from one level to the other. The rotunda is covered with white PVC pyramidal covering (13% transmissivity) open at the top 12 as shown in Figure 6.

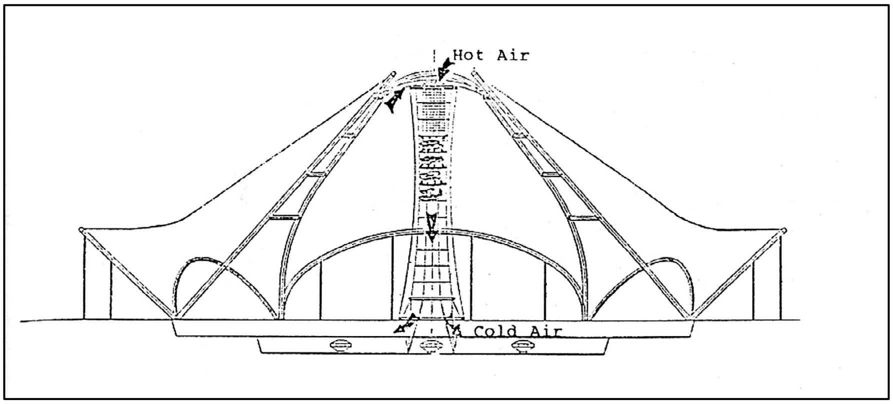

Figure 6: Air handling units in the floor and tower (Source: Alvarez [12,12])

Table 1 Cooling Techniques implemented within the Bioclimatic Rotunda of Expo '92

Criteria	Actions	
Control of Solar Radiation	Covering (Direct and diffuse) Confinement (reflection of solar radiation)	
Reduction of surrounding surface temperatures	Cooling the covering by irrigation Cooling the pavement using running water (wasn't used at the end, as proven to be insufficient, and will cause changes to the infrastructure. Cascades	
Lowering the temperature of the air	Evaporative cooling	Air handling unit (mechanical evaporative cooling • Micronizers in tower • Micronizers in trees • Micronizers in peripheral rings: Wet barriers

The rotunda houses a considerable number of techniques and strategies aimed at the thermal conditioning of outdoor spaces. A number of natural air cooling techniques were implemented; most of them based on the evaporative cooling which takes place when air and water are put into contact. These strategies are briefly discussed in Table 1.

The main concept of the micronizers used was droplet evaporation that helps the cooling of the air. The group of micronizers presented in Table 1 were a successful tool that helped the air to cool down after crossing them 12 are seen in Figures 7 and 8. It worked as a barrier that prevented the wind from neutralizing the cooling of the air, and pre-cooled the air before it entered the occupied area.

Figure 7: Micronizers in tower; micronizers in trees, micronizers in peripheral rings respectively (Source: Alvarez [12])

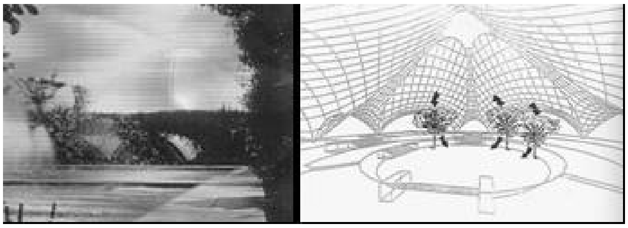

Figure 8: The bioclimatic rotunda 18; Mechanism of micronisers in tress 12

As the rotunda served as a full scale pilot project, the conclusions drawn from the analysis of its modelling and monitoring was of great aid to the understanding of passive cooling of fabric membrane semi- enclosed spaces. A simultaneous analysis was carried out for the temperature of the covering, temperature of the air and the air velocity.

The conclusions obtained from this study stressed that any subsystem used for fulfilling any of the criteria presented in Table 1 should always be evaluated in terms of the ultimate objective of that subsystem (fulfilment of a given level of comfort), comparing it with other alternative subsystems. Also the modelling and simulation play a crucial role in the effective evaluation of subsystems and in the extrapolating of the results to other applications, along with monitoring and simulation. In short experimentation alone does not lay solid basis for environmental predictions and applying design guidelines, and need along side with it computer simulation and analysis 13.

The results showed that it was possible to condition an outdoor space using natural cooling techniques at lower costs. These techniques proved not only to be compatible with the functional and aesthetic criteria of the design, but also of undeniable ecological value.

4.3 Assembly Tent in Malaysia

This is a mobile adaptable tent structure that provides the best possible climatic conditions for a hot and tropical climate, by use of a multi-layer membrane roof with low inside surface temperatures. Although, this paper is concerned with application in hot arid climates, the authors found that there is a good potential in the external form providing environmental solutions in this project that can be easily applied to hot arid regions. Based on investigations carried out in Malaysia into the use of membrane structures under tropical conditions, a fabric membrane tent roof was designed to provide a broad covering for open-air assemblies. The structure is designed such as to have large wind catching openings at the perimeter and an air ventilation opening at the tent top as shown in the pictures presented in Figure 9. Large openings at the sides and a central outlet allow a continuous flow of cross ventilation and assist the structure to function efficiently despite high humidity, high temperatures and frequent rainfall. External air movements support the internal ventilation and provide relief against the heat.

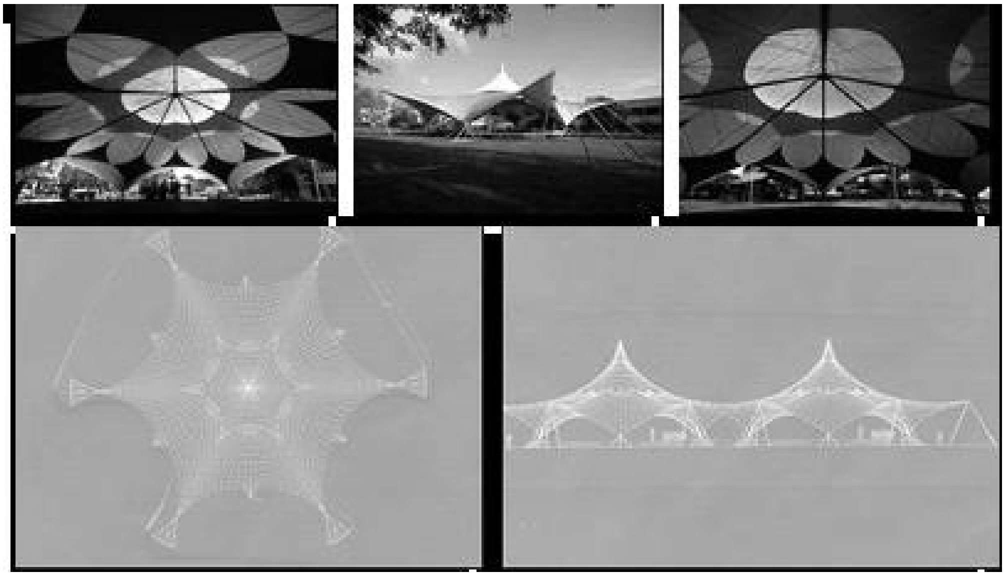

Figure 9: Assembly Tent in Malaysia, with plan and section of the structure (photo courtesy of Bodo Rasch)

The structural framework consists of six struts supported on tripod elements, with a central mast at the upper level which is seen in the plan and section presented in Figure 9. The roof covers an area of 500 m2 without intermediate columns 14. The membrane and the struts were hoisted into position by means of a central assembly mast, which allowed the tent to be erected without a crane. This auxiliary mast was removed after the struts had been fixed at the top. Six outer masts and the tripod supports, which are adjustable in height, transmit wind loads to the ground via pins anchored in the earth. Sprung stays absorb the loads of strong gusts of wind.

The main section was constructed in a multi-layer form which provides both an attractive structure and assists in ventilation. An outer skin of aluminium-coated mesh fabric 30cm above the weatherproof layer screens the latter against overheating. The central, umbrella-like section of the roof is structurally united with the main area. The use of multiple layers allows the passage of air between the double membranes providing air space ventilation. This form of construction provides protection against the rain and facilitates the removal of warm air and moisture. The raised floor, which is independent of the load-bearing structure, protects against rising damp and also helps to improve the ventilation, utilizing the thermal mass effect.

5. HYPOTHETICAL APPLICATION OF TMS AS MICROCLIMATE MODIFIERS IN THE LANDSCAPE

Although it was understood that tensile architecture began with the use of natural materials, animal hides and woven plants, it is only within the past 30 years that designers have discovered the merits and advantages of using TMS in the microclimate or the landscape. Besides the opportunities for visible aesthetic, applications for fabrics in the landscape, there is an immediate benefit of providing shading for public spaces as well as controlling the wind speed.

Uses of fabrics can range from providing shade, wind control, spatial definition, and creation of identity and public art, which can be seen as functional art on both large and small scale. Fabric membranes were used at a number of different projects as the one presented in this paper to provide adequate shade, channel breezes and define space. While these projects provide modern pieces of architecture they do point out new opportunities for using fabrics in microclimate modification as well as landscape design. In most of these projects, the fabric structures were dramatic and well designed and contributed considerably to the image of these places and events.

It is believed that there is a need for further research to be undertaken into this field, in order to understand the effect the form of the structure will have on its environmental behaviour and be able to have a proper prediction of its post occupation environmental behaviour.

6. SUMMARY

In this paper the environmental behaviour of TMS is discussed briefly and the possible use of the fabric's topology and geometry particularly to enhance occupants comfort level within the enclosed or semi-enclosed space is discussed. Thus, the need for further research in this area is suggested as a route to fully realising the potential benefits offered by these structures. The paper explored how the unique nature of the TMS topology can be effectively designed to achieve better environmental performance. Features like topography, local climate, sun and site orientation and wind should all have a significant role in the form finding of a tensile structure. The possibility of using the fabrics topology to enhance the ventilation rates and the climatic performance of the interiors along with the employment of a number of architectural strategies commonly applied to conventional buildings were discussed.

The second part of this paper provided some case studies of the built environment where the form and topology of the fabric materials were used to assist in the ventilation of the space and enhance the comfort level of the occupants within the enclosed or semi-enclosed space.

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